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INTRODUCTION TO PARTICLE PHYSICS with HIGHLIGHTS ON THE ASTROPARTICLE ASPECTS

Antonio Masiero
Univ. of Padova
and
INFN, PADOVA

CONTENT

1. STANDARD MODEL OF PARTICLE PHYSICS: CRITICAL REASSESSMENT
2. GRAND UNIFICATION, SUPERSYMMETRY, DYNAMICAL SYMM. BREAKING AND EXTRA-DIM.
3. NEUTRINO MASSES
4. ASTROPARTICLE HINTS FOR NEW PHYSICS:
   - DARK MATTER (DARK ENERGY?)
   - MATTER-ANTIMATTER ASYMMETRY
   - INFLATION

1. STANDARD MODEL

<u>SPONTANEOUSLY BROKEN</u> <u>GAUGE</u> THEORY

~~SPON~~ SYMMETRIES :
$$\begin{cases} \text{CONTINUOUS} \begin{cases} \text{GLOBAL} \\ \text{LOCAL (GAUGE)} \end{cases} \\ \text{DISCRETE} \\ \text{(ex. PARITY)} \end{cases}$$

ex: $(i\not\partial - m)\psi(x) = 0 \qquad \not\partial \equiv \gamma^\mu \partial_\mu$

DIRAC EQ. → free electron invariant

under : $\psi(x) \rightarrow e^{i\alpha}\psi(x)$

α const. ↗ U(1) GLOBAL Symm.

U(1) LOCAL (GAUGE) Symm :

α const $\rightarrow \alpha(x)$

↑ param. of the U(1) rotation is a function of $x(t, \vec{x})$

to enforce the local U(1) symm :

$\partial_\mu \rightarrow D_\mu \equiv \partial_\mu - ieA_\mu$

↳ covariant deriv. ↳ "compensating" vector (gauge) field

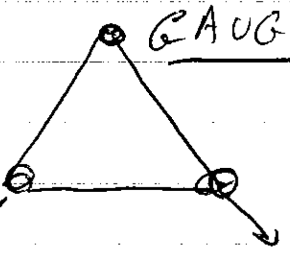
$$A_\mu(x) \underset{U(1)}{\rightarrow} A_\mu(x) - \frac{i}{e}\partial_\mu \alpha(x)$$

$(i\not{D} - m)\psi(x) = 0$ invar. under local U(1)

$\Rightarrow$ interaction term : $e\bar{\psi}\gamma^\mu\psi A_\mu$

↗ interaction eletron-photon fields

$F_{\mu\nu}F^{\mu\nu}$ → kinetic term for the photon



→ all infinities reabsorbable in a finite number of free parameters

SPONTANEOUS SYMMETRY BREAKING

↓ $\mathcal{L}$ (lagrangian) respects a symm., but the vacuum of the theory does NOT respect it

ex: $V = \mu^2\varphi\varphi^* + \lambda(\varphi\varphi^*)^2$

V invar. under $\varphi(x) \rightarrow e^{i\alpha}\varphi(x)$

if $\mu^2 < 0$ → $\langle 0|\varphi|0\rangle \neq 0$

↳ vacuum is NOT U(1) invariant

↓ order param. of the phase transition

$G \xrightarrow[\text{spont. break.}]{} G'$

if G global → generators of G/G'
↳ Goldstone bosons (massless scalars)

if $\boxed{\text{G LOCAL}}$ → $\boxed{\text{HIGGS MECHANISM}}$

Goldstone bosons "eaten up" by the gauge bosons of G/G' to become their longitudinal components

⟹ gauge bosons of G/G' become MASSIVE, their mass being $\propto \langle 0|\varphi|0\rangle = v$ and to their gauge coupl. const.

$$\boxed{G_{\text{ST. MODEL}}} \equiv \begin{array}{ccccc} SU(3)_c & \otimes & SU(2)_L & \otimes & U(1)_Y \\ \downarrow & & \downarrow & & \downarrow \\ 8 \text{ gluons} & & W_1^\mu, W_2^\mu, W_3^\mu & & B^\mu \end{array}$$

hyperchar
gauge boso

GAUGE SYMMETRY

MATTER FERMIONS

	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$(u^c)_L$	$(d^c)_L$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$(e^c)_L$
$SU(3)_c$	3	$\bar{3}$	$\bar{3}$	1	1
$SU(2)_L$	2	1	1	2	1
$U(1)_Y$	1/6	$-2/3$	$+1/3$	$-1/2$	$1/2$

$$Q = T_3 + Y$$

$$\mathcal{L}_{int} = g_1 J^\mu B_\mu + g_2 J_i^\mu W_{\mu i} + g_3 J_a^\mu A_{\mu a}$$

$$i = 1, 2, 3 \qquad a = 1, \dots, 8$$

$$J_\mu^i = (\bar{u}\ \bar{d})_L \gamma_\mu \left(\frac{\tau_i}{2}\right) \begin{pmatrix} u \\ d \end{pmatrix}_L + (\bar{\nu}_e\ \bar{e})_L \gamma_\mu \left(\frac{\tau_i}{2}\right) \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

...

$$W_\pm^\mu = \frac{1}{\sqrt{2}} \left(W_1^\mu \mp i W_2^\mu \right)$$

As long as G_{SM} unbroken

$\Longrightarrow$ all gauge bosons + fermions are MASSLESS

	SU(3)	SU(2)	U(1)
$\begin{pmatrix}\phi^0\\ \phi^-\end{pmatrix} \equiv \Phi$ SCALAR	1	2	$-1/2$

↳ <u>elementary</u> scalar Higgs doublet or "<u>composite</u>" scalar coming from some "strong dynamics"

$$\langle \Phi \rangle = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$$

$$\begin{array}{c} * \\ \\ * \end{array} \quad \boxed{\begin{array}{c} SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \\ \Big\downarrow \; \langle \Phi \rangle \\ SU(3)_c \otimes U(1)_{em} \end{array}} \quad \begin{array}{c} * \\ \\ * \end{array}$$

$$M^2_{W^\pm} = \frac{g_2^2 v^2}{4}$$

$$\frac{1}{8} v^2 \begin{pmatrix} W_3^\mu & B^\mu \end{pmatrix} \begin{pmatrix} g_2^2 & -g_2 g_1 \\ -g_2 g_1 & g_1^2 \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

$$Z_0^\mu = \cos\theta_W \, W_3^\mu - \sin\theta_W \, B^\mu$$

$$A^\mu = \sin\theta_W \, W_3^\mu + \cos\theta_W \, B^\mu$$ → <u>photon</u>

$\theta_W \equiv$ weak angle or Weinberg angle

$$M_Z^2 = \frac{1}{4}\left(g_2^2 + g_1^2\right) v^2 \qquad M_A^2 = 0$$

* $\boxed{\text{MASSES}}$: $\begin{cases} \text{FERMIONS} \\ \text{GAUGE BOSONS} \\ \text{SCALARS} \end{cases}$

FERMIONS : $\xrightarrow{\psi_L} \times \xrightarrow{\psi_R}$ or $\xrightarrow{\psi_L} \times \xleftarrow{(\psi^c)_L}$

↓ $SU(2)_L \otimes U(1)_Y$ breaking

2+2 d.o.f. → DIRAC MASS
ψ_L ψ_R

$\xrightarrow{\psi_L} \times \xleftarrow{\psi_L}$ only 2 d.o.f.
Majorana Mass

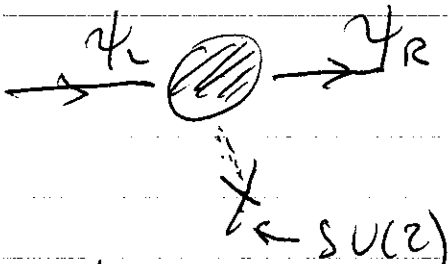
for charged fermions → forbidden by Q_{el} conserv.

for neutrinos → $\xrightarrow[\nu_L]{} \mid \xleftarrow[\nu_L]{}$

↓ $SU(2)_L$ breaking need triple
but in SM only Φ double

FERMION MASSES ARISE ONLY WHEN $SU(2)_L \times U(1)_Y$ IS (SPONTANEOUSLY) BROKEN

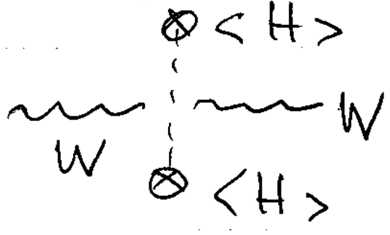
$h\, \bar{\psi}_L \psi_R H \underset{\text{after SSB}}{\longrightarrow} h\, \bar{\psi}_L \psi_R \langle H\rangle \rightarrow m_\psi = h \langle H \rangle$

Radiative Corrections 

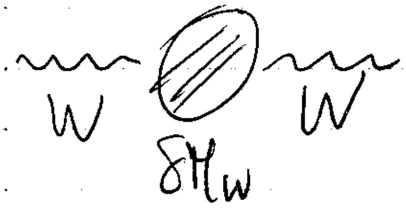
← SU(2) breaking

Fermion Masses cannot exceed the ELW. SYMM. BREAKING SCALE $O(v)$

GAUGE BOSON MASSES:



M_W ARISES WHEN $SU(2)_L \otimes U(1)$ is (SPONTANEOUSLY) BROKEN

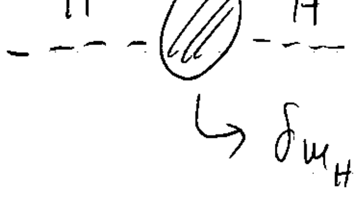


δM_W is limited by the elw. symm. breaking scale

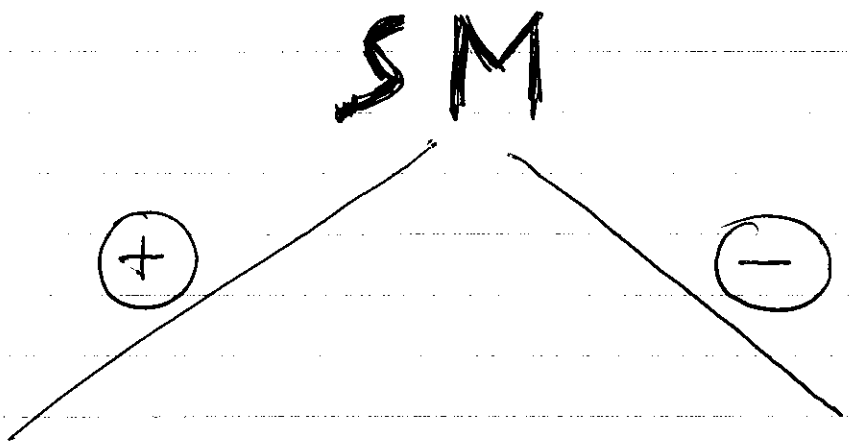
SCALAR MASSES

$$\mu^2 HH^\dagger + \lambda (HH^\dagger)^2$$

$\Rightarrow$ $SU(3) \times SU(2) \times U(1)$ does $\boxed{\text{not}}$ prevent the presence of scalar masses



δm_H can be (much) larger than the elw. symm. breaking scale



1) SPONT. BROKEN GAUGE THEORY → renormalizability

2) GREAT SUCCESS WITH ALL EXP. TESTS:

- High Energy Physics (in particular LEP, but $Z \to b\bar{b}$ ...)
- FCNC, CP≠
  OK, but $\sin 2\beta$ problem(s) ...
- High precision tests
  OK, but $(g-2)_\mu$

3) B and L are AUTOMATICALLY CONSERVED

1) FLAVOR PROBLEM
(no "rationale" behind fermion masses and mixings (just free param.)

2) (LACK OF) UNIFICA
OF INTERACTIONS
g_1, g_2, g_3
GRAVITY OUT

3) HIERARCHY PROBLEM

HIERARCHY PROBLEM

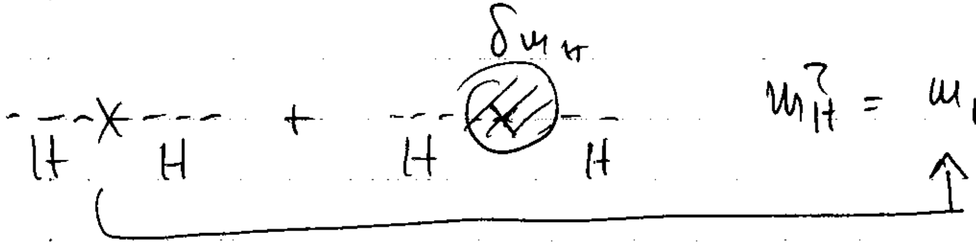
1). The "FUNDAMENTAL" Aspect:

WHY $M_W \ll M_P$

$\hookrightarrow$ ~ 17 orders of magnitude

2) The "TECHINICAL" Aspect:

once one arranges the param. of the Lagrangian so that $M_W \ll M_P$ how can one "stabilize" such choice against radiative corrections



$$m_H^2 = m_H^{0\,2} + \delta m_H^2$$

if $\delta m_H^2 = A M_X^2 + B M_X^2$ with $M_X \gg M_W$

need fine-tuning of A and B so that $m_H^0 + \delta m_H^2 \sim O(m_H^{0\,2}) \sim O(v^2)$

fine-tuning $\rightarrow$ | NATURALNESS PROBLEM |

GRAND UNIFICATION

$$\frac{d\alpha_i}{d\ln q^2} = b_i\,\alpha_i^2 + O(\alpha_i^3)$$

$$\begin{cases} b_3 = -\dfrac{1}{4\pi}\left[\dfrac{11}{3}\cdot 3 - \dfrac{4}{3}\, n_{gener.} + \underset{\uparrow\ \text{scalars}}{\cdots}\right] \\ b_2 = -\dfrac{1}{4\pi}\left[\dfrac{11}{3}\cdot 2 - \dfrac{4}{3}\, n_{gener} + \cdots\right] \\ b_1 = -\dfrac{1}{4\pi}\left[-\dfrac{4}{3}\, n_{gener.} + \cdots\right] \end{cases}$$

with Y defined by $Q = T_3 + \sqrt{\frac{5}{3}}\,Y$

$$\frac{1}{\alpha_i(q^2)} = \frac{1}{\alpha_i(M_X^2)} + b_i \ln\left(M_X^2/q^2\right)$$

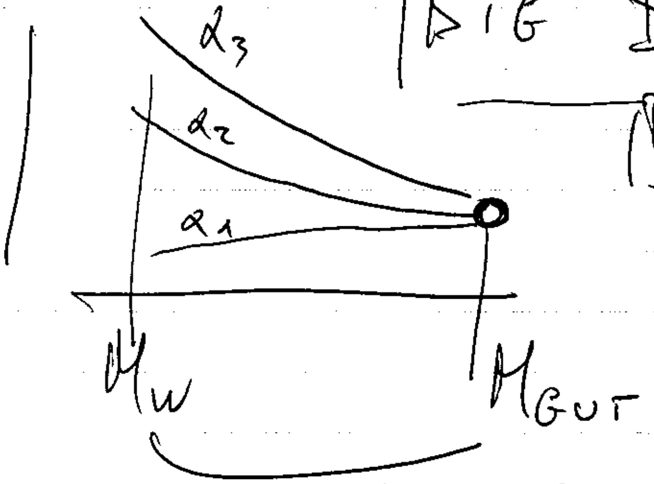
ask for: $\alpha_1(M_X^2) = \alpha_2(M_X^2) = \alpha_3(M_X^2) \equiv \alpha_G$

unknown: α_G, M_X, $\sin^2\theta_W$ (or α_3)

$\Rightarrow$ possible to DETERMINE (predict) a LOW EN. PARAM

$\sin^2\theta_W \approx 0.2$ in the right ball-park!

But with today precision: α_S predicted several standard deviations away from the correct value $\Rightarrow$ need some modification from



BIG DESERT PICTURE

13 orders of magnitude

NEED some NEW PHYSICS between M_W and M_{GUT} to modify the slopes of the 3 curves to obtain the correct value of α_S (or $\sin\theta_W$) as the low-energy prediction!

Ex: new SUSY particles at $\sim M_W$

HOW TO COPE WITH THE HIERARCHY PROBLEM

DYNAMICAL SYMMETRY BREAKING

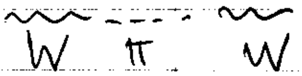
Ex. Chiral symm. in QCD

u
d
$SU(2)_L \times SU(2)_R$ symm.

$\langle u\bar{u}\rangle \neq 0$
$\langle d\bar{d}\rangle \neq 0$

$SU(2)_L \times SU(2)_R$
$\downarrow$
$SU(2)_V$

3 "Goldstone bosons" $\pi^\pm, \pi^0$



$M_W \propto f_\pi$

$\pi^\pm, \pi^0$ longit. comp. of $W^\pm, Z^0$

→ rescaled QCD
Technicolor
with $F_\pi \sim 1\,\mathrm{TeV}$

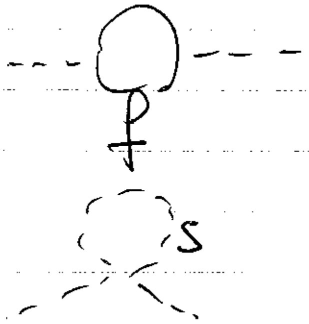
(LARGE) EXTRA DIMENS.

↓

No hierarchy Problem because M_P is <u>not</u> $\gg M_W$

M_P can be $\gtrsim M_W$ but gravity small because part of its flux lines are dispersed into extra dim.

LOW-ENERGY SUPERSYMM. (SUSY)



if $m_f = m_s$
and $g_f = g_s$
↓
cancellations need F ⟺ Bosons symm.

SUSY

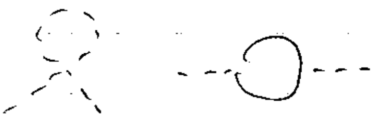
$\begin{pmatrix} F \\ B \end{pmatrix}$ broken at ~ TeV

LOW-ENERGY SUSY

SPIN 1/2		spin 0		spin 1
q	$\rightarrow$	$\tilde{q}$		
ℓ	$\rightarrow$	$\tilde{\ell}$		
$\tilde{W}$	$\leftarrow$		$\leftarrow$	W
$\tilde{H}$	$\leftarrow$	H		

$\begin{pmatrix} B \\ F \end{pmatrix}$ as long as $B \underset{SUSY}{\leftrightarrow} F$ is unbroken

$m_B = m_F$



← $\delta m_H = 0$

but no evidence of $\tilde{e}$ with mass = 1/2 MeV

$\Rightarrow$ NEED $\boxed{\text{SUSY BREAKING}}$

if $M_S \equiv$ scale of SUSY breaking

$\Rightarrow |m_B^2 - m_F^2| = O(M_S^2)$

→ to realize a "protection" of Higgs mass at the TeV scale $\Rightarrow$ $\boxed{M_S \sim O(\text{elw. breaking scale})}$

$\Rightarrow$ SUSY particles are at the 100 GeV - 1 TeV scale ! Possible to detect (some of) them at LHC !!!

Baryon and Lepton Numbers in SUSY

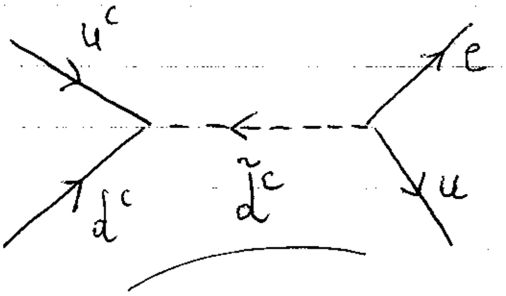
$$W = h_U Q H_u u^c + h_D Q H_d d^c + h_L L H_d e^c$$
↳ superpotential

⇒ New terms: LLe^c $u^c d^c d^c$ QLd^c

$LLe^c \rightarrow L \neq 0$

$u^c d^c d^c \rightarrow B \neq 0$

$QLd^c \rightarrow L \neq 0$



$p \rightarrow e^+ + \pi^0$

$\tau_p > 10^{33}$ yrs

⇒ $M_{\tilde{d}^c}$ should be $> 10^{14} - 10^{15}$ GeV to satisfy the above bound on τ_p

but $M_{\tilde{d}^c} \sim O(1\,\text{TeV})$ to invoke SUSY for the gauge hierarchy problem

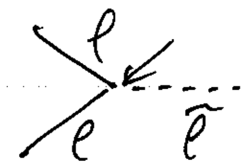
⇒ too fast (by far!) p-decay if $L \neq 0$ and $B \neq 0$ terms in W are allowed. ⇒ Impose ADDITIONAL SYMMETRY to forbid $L \neq 0$ and/or $B \neq 0$

Simplest possibility :

DISCRETE SYMMETRY * $\boxed{\text{R-PARITY}}$ * reading :

$\Rightarrow \begin{cases} +1 \text{ on ordinary particles} \\ -1 \text{ " SUSY partners} \end{cases}$

ex: $LLe^c \Rightarrow$



$(+1)\cdot(+1)\cdot(-1)$
this vertex is forbidden by R-parity.

R-parity is <u>NOT</u> the only ~~choiche~~ choice to prevent too fast p-decay

$\Rightarrow$ alternatives : discrete symm. $\begin{cases} \text{L-parity forbidding } LLe^c \\ \text{B-parity " } QLd^c, u^c d^c d^c \end{cases}$

<u>N.B.</u> : to allow for $\not{B}$ p-decay need <u>BOTH</u> <u>B</u> <u>and</u> <u>L</u> VIOLATIONS –

However, imposing L- or B- parity $\Rightarrow$ need for (strong) suppressions of the new $L \neq$ or $B \neq$ violating operators (because of FCNC, m_ν, ...)

$\Rightarrow$ "superiority" of R-parity !

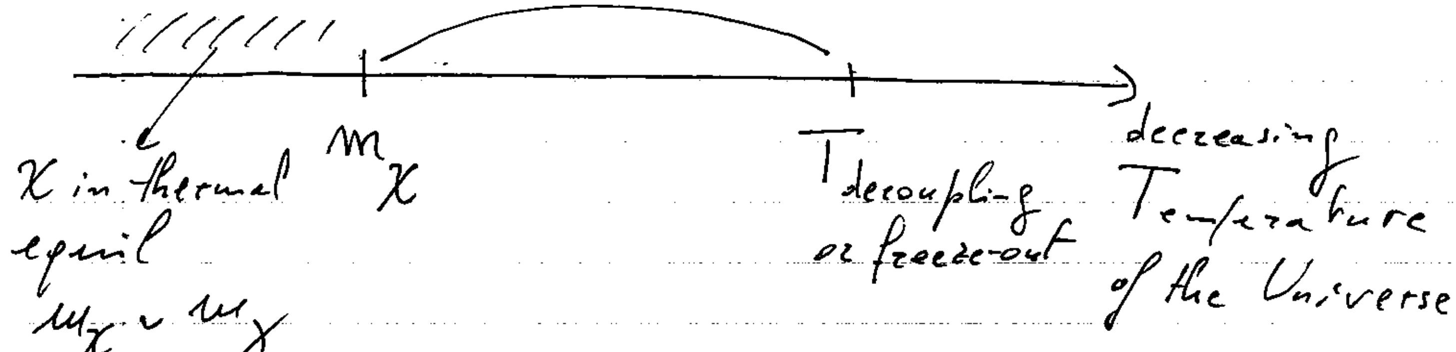
Consequences of R-parity:

- SUSY particles are created or destroyed in pairs
- **LIGHTEST SUSY PARTICLE (LSP) IS STABLE !** *

LSP and WIMPS
weakly interacting massive particles

χ WIMP

$e^{-m_\chi/T_{\text{decoupling}}}$ decrease in the # of W



$T_{\text{decoupl.}}$: compare H = expansion rate of the Univ. $\sim g_* \frac{T^2}{M_P}$

with $\Gamma_{\text{interact.}}$ rate of χ with other part.

e $\Gamma_{\text{annih.}}$ → changes # χ

when $\Gamma_{\text{annih}} < H$ χ decouples

Which SUSY particle is the LSP ?

It depends on the SUSY model

High Scale SUSY$\!\not\,$

in a HIDDEN SECTOR

GRAVITY MEDIATION

$m_{\text{gravitino}} = \frac{F}{M_P} \sim 10^2\text{-}10^3\,\text{GeV}$

GAUGE MEDIATION

$m_{\text{gravitino}} = \frac{F}{M_P} \sim 10^2\text{-}10^3\,\text{eV}$

COMMUNICATION OF SUSY$\!\not\,$

in the OBSERVABLE SECTOR

Here F ~ 10^{10} GeV − 10^{11} GeV

Possibly : lightest neutral SUSY fermion

$\underbrace{\tilde{H}_u^0 \quad \tilde{H}_d^0 \quad \tilde{W}_3 \quad \tilde{B}}$ neutralinos

lightest eigenvector of their 4x4 mass matrix

$\tilde{q} \to q + \tilde{\chi}$

jets + missing energy

F ~ 10^4 - 10^5 GeV

gravitino LSP

important

NLSP (next-to-LSP)

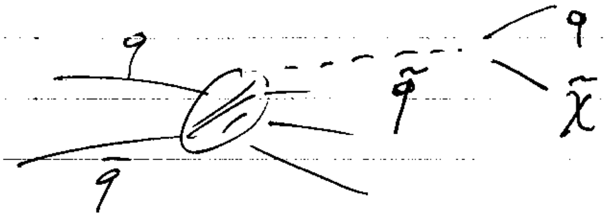
ex :

$\chi \to$ gravitino + γ

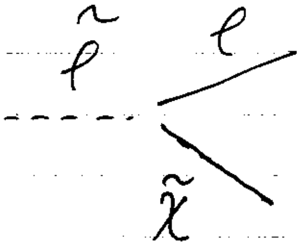
neutralino

γ + missing energy

New vertices → interactions



or



bounds on the masses of SUSY particles:

Tevatron $\underline{m_{\tilde q}, m_{\tilde g}} \gtrsim \underline{200 \text{ GeV}}$
→ gluinos

LEP : $\underline{m_{\tilde\ell}, m_{\tilde\chi^+}} > \underline{100 \text{ GeV}}$
↪ charginos
$\tilde W \tilde H^+$ mixing

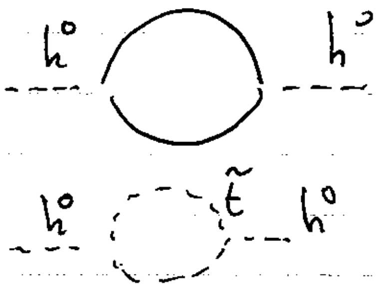
In SUSY version of the SM:

2 Higgs doublets H_u H_d

physical Higgs scalars : $\left\{ \begin{array}{l} h^0, H^0, A^0 \\ H^+ \leftarrow \text{charged Higgs!} \end{array} \right.$

$m_{h^0} < m_{Z^0}$ at Tree level!

rad. corrections (ex:



)

⇒ given the large m_t

rad. corr. can be rather large

in SUSY:

$$m_{h^0} \lesssim \underline{130-135}\ \text{GeV}$$

(firm) prediction of low-energy SUSY

present bound from LEP II

$$m_{h^0} > 114\ \text{GeV} \quad !$$

if LHC does not find a higgs as light as 130-135 GeV

$\Rightarrow$ need some rather special variants of low-en. SUSY version of SM or rule out low-en. SUSY -

Minimal supersymmetrization of the SM

MSSM: minimal amount of (super-)fields

<u>how</u> <u>many</u> <u>param. in MSSM</u> ?

in general: ~~different~~

~~SUSY SM~~ $\mathcal{L}_{MSSM} = \underbrace{\mathcal{L}_{SUSY\ SM}} + \left(\text{soft SUSY breaking terms}\right)$

$$\Uparrow$$

"soft" ⇒ these SUSY≠ terms do not introduce "dangerous" QUADRATIC diverg

soft SUSY≠ $\left\{ \begin{array}{l} \underline{\text{masses for scalars}} \\ \underline{\text{bilinear scalar terms}} \\ \underline{\text{gaugino masses}} \end{array} \right.$

MSSM more than 100 new PARAM. in addition to those of the SM!

⇒ most of this enormous param. space is already ruled out by <u>FCNC and CP≠ constraints</u>

to reduce this very large param. space (drastic) assumptions on the structure of the soft breaking terms:

CONSTRAINED MSSM (CMSSM)

$$\begin{cases} m_0 : & \text{universal mass for all s-fermions and Higgs} \\ m_g : & \text{universal gaugino mass} \\ A : & \text{universal trilinear coupling} \end{cases}$$

\+ μ param : $\mu H_u H_d \longrightarrow$ superfields

\+ B " : $B\mu H_u H_d \longrightarrow$ scalar fields

\+ imposing elw. radiative breaking

only <u>4 param.</u> !

ex-: m_0, m_g, A and B

or introducing $\tan\beta \equiv \frac{v_u}{v_d}$ $\left(v_u = \langle H_u \rangle \;\; v_d = \langle H_d \rangle \right)$

m_0, $m_{\tilde{g}}$, A, $\tan\beta$ –

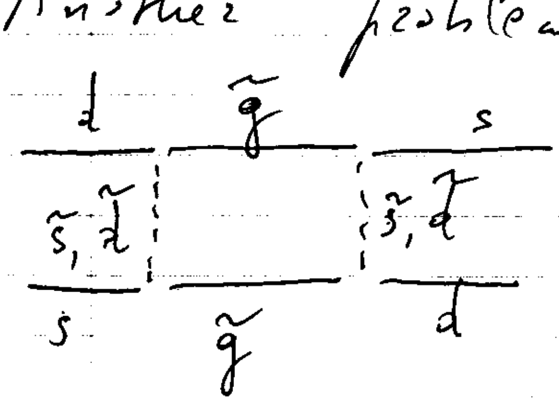
What are the SUSY predictions concerning the SUSY masses?

The answer is model dependent (it depends, in particular, on the soft SUSY ≠ terms)

⇒ given that $m_h > 114$ GeV and $m_{\chi^+} > 100$ GeV

we already need some tuning on the SUSY param. ⇒ i.e. without any tuning we should have already seen some SUSY particles, in particular at LEP II!

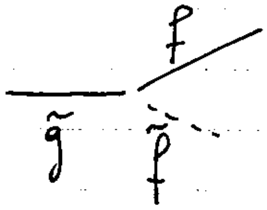
Another "problem" for low-energy SUSY:



⇒ Δm_K

SUSY contributions to FCNC tend to be too large!

if one takes generic squark mass matrices
⇒ one exceeds by 3-4 orders of magnitude the exp. results on FCNC (es. Δm_K, $b \to s\gamma$, Δm_{B_d}, Δm_{B_s}, ...) + FC CP violation (ex.: ε_K, ε'/ε, $A_{CP}(B \to J/\psi K_S)$, ...

⇒ 

need that the fermion and s-fermion mass matrices are simultaneously diagonalized

(this occurs, for instance, if $m_{\tilde f} = m_0 \mathbb{1}$, $\mathbb{1}$ in generation space)

LHC will succeed to explore masses of colored SUSY particles (gluinos, squarks) up to ~ 2 TeV + Higgs mass up to several hundred GeV + non-colored s-particles up to 200-300 GeV ⇒ decisive test for low energy SUSY!